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Design of Power Distribution Control and Stochastic Observers for Flux Mapping for Advanced Heavy Water Reactor

Ph.D. Workplan

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Design of Power Distribution Control and Stochastic Observers for Flux Mapping for Advanced Heavy Water Reactor

1) A brief resume of proposed problem

In large nuclear reactors, such as the Advanced Heavy Water Reactor (AHWR), core neutron flux distribution needs to be continuously monitored to generate reference signals required for reactor power control, and for display to the operator. This task is accomplished by an online Flux Mapping System, which employs a suitable algorithm to estimate the core flux distribution from the readings of large number of (~ 200) in-core detectors. Most of the flux mapping algorithms available today employ Flux Synthesis method, Internal Boundary Condition method, and the method based on simultaneous least squares solutions of neutron diffusion and detector response equations. However, recently the flux-mapping problem in AHWR is successfully formulated as an optimal estimation problem that can be solved using the discrete Kalman filtering technique which employs a space-time kinetics model of the reactor. In similar lines, it is proposed to investigate the feasibility of employing other stochastic observer techniques such as other variants of Kalman filter, H-infinity filter, sliding mode observer etc. in flux mapping of AHWR.

The foremost problem encountered in control, analysis and design of a large reactor is the model development. Nuclear reactors of small core size are adequately represented by the well-known point kinetics model which depicts the dynamics of the core averaged neutron flux/power and the associated delayed neutron precursor groups. For large reactors, however, this model will not suffice since the flux shape in large reactor undergoes variations which the point kinetics model is unable to capture. Hence for large nuclear reactors, it is essential to adopt more detailed space-time kinetics models for analysis. Therefore it becomes essential to develop, a suitable mathematical model which captures all the essential properties of the reactor core, and then to develop and implement a computer code in the form of off-line computer programs to study the behavior of plant in various postulated accident conditions. And thus development of some strategies such as terminal sliding mode control and higher order sliding mode control is proposed for power distribution control of advanced heavy water reactor.

2) Introduction to proposed research topic.

Flux Mapping Problem: In large nuclear reactors, such as the Advanced Heavy Water Reactors (AHWR), the three-dimensional (3D) in-core power distribution changes continuously and complexly due to the movement of control rods, the feedback effects of reactivity, and the burn-up of fuel etc. Therefore, to ensure safe, reliable and economic operation of nuclear power plants, operating power of the reactor should be maintained close to the demand power. Thus, this would demand the core neutron flux distribution to be continuously monitored and displayed to the operator and at the same time, the core flux distribution should closely match the desired flux distribution. This task is accomplished by an online Flux Mapping System (FSM), which employs a suitable algorithm to estimate the core flux distribution from the readings of many in-core detectors [1].

Basically, there are three types of detectors have been developed to monitor -in-core power distribution in nuclear reactors, ex-core neutron detectors, movable detectors and fixed in-core detectors [2]. Ex-core detectors provide the information of in-core power on the axial direction. However, this detector provides low reliability of measurement when influenced by noise. Movable detectors use movable detector system which is required to implement periodically to obtain high reliability in in-core power distribution measurement. Therefore, these detectors cannot provide continuous real-time information. Therefore, to overcome the limitations of above two detectors, another type of detector called as fixed in-core detector has been developed which provide information of in-core power distribution with higher reliability. BEACON [3] and GNF-ARGOS [4] are the example of on-line in-core power distribution monitoring systems.

The main idea behind this monitoring system is to first calculate 3D power distribution online and then adapt the calculated power distribution using detector weighing function based on detector readings. However, this demands

large number of experimentations to be performed to verify the reliability of the detector weighing function. Furthermore, adaptation mechanism gets failed when the weighing function reaches zero at the region far from the detector [5].

By considering above drawbacks mentioned in the literature review which follows, recently the flux mapping problem in AHWR is successfully formulated as an optimal estimation problem [14], which can take care of both time-varying phenomena and random errors in the detector readings. The estimation problem can be solved using the discrete Kalman filtering technique which employs a space-time kinetics model of the reactor. In this approach, the Kalman gain equations have been decoupled into separate sets of equations for the slow and fast subsystems and solved separately since solving the Kalman filtering problem in a straightforward manned is not successful due to severe numerical ill-conditioning caused by the simultaneous presence of slow and fast phenomena typically present in a nuclear reactor [15-19]. This situation can easily be handled by singular perturbation analysis and two time-scale methods. Some singular perturbation methods for Kalman filter design can be found in [20-24].

In similar lines, it is proposed to investigate the feasibility of employing other stochastic observer techniques such as other variants of Kalman filter, H-infinity filter, sliding mode observer etc. in flux mapping of AHWR.

Power Distribution Control Problem: Fission reactions taking place in the reactor core give birth to numerous nuclear species. One of the isotopes is xenon (^{135}Xe), which requires attention, due to the large cross section of thermal neutron absorption. A small portion of ^{135}Xe is created directly in fission but the major part results from the radioactive decay of iodine (^{135}I). Furthermore, it decays at a comparatively slower rate than ^{135}I does. Therefore an abrupt increase in neutron flux in the reactor core decreases the concentration of ^{135}Xe, which further increases neutron flux. This persists for a few hours and then an opposite action takes place, in which the increased neutron flux results into formation of more Xenon which in turn reduces the neutron flux. In this way, oscillations of the neutron flux are initiated by ^{135}Xe [34, 36]. In small nuclear reactors, these oscillations can be effectively controlled by appropriate control rod algorithm and hence do not pose serious concern in operation and control. However, in 'large' nuclear reactors where physical size is quite a lot of times the neutron migration length, spatial oscillations are significantly important. If these oscillations in the spatial power are not controlled, the power density and the rate of change of power at some positions in the core may go beyond their respective thermal limits, and may result in fuel failure. Therefore, in large thermal nuclear reactors, it becomes essential to utilize automatic power distribution control system, apart from the control of the total power of the reactor. The main intention is to maintain the core power distribution close to a preferred shape.

The foremost problem encountered in control analysis and design of a large reactor is the development of mathematical model. Nuclear reactors of small core size are adequately represented by the well-known point kinetics model which depicts the dynamics of the core averaged neutron flux/power and the associated delayed neutron precursor groups. For large rectors, however, this model will not suffice since the flux shape in large reactor undergoes variations which the point kinetics model is unable to capture [34]. Therefore, for large nuclear reactors, it is essential to adopt more detailed space-time kinetics models for analysis. Thus, it becomes essential to develop a suitable mathematical model which captures all the essential properties of the reactor core and then to develop and implement a computer code in the form of an offline computer algorithm to regulate the behavior of system in various proposed transient situations.

As far as the power distribution control is concerned, it is important to note that the model of a nuclear reactor belongs to a special class of systems called singularly perturbed systems. The simultaneous presence of both the slow as well as fast varying dynamical modes could cause ill-conditioning of the problem. Fortunately, the rich literature on singular perturbations and control makes it feasible to analyze such systems and design the controller. Using these techniques, model of the nuclear reactor can be transformed into a proper form whereby stiffness is completely removed. Once, this has been done, numerous approaches are available for carrying out the design of spatial power distribution control systems.

Feedback of total power (or core averaged power) is normally sufficient for control of small or medium size nuclear reactors, whereas large reactors may necessitate feedback of spatial power distribution along with the total power feedback for efficient spatial control. However, a major limitation of the static output feedback is that it may not guarantee arbitrary pole placement. Hence, static output feedback is not preferable as it may not meet all the

performance specifications. Employing dynamic output feedback may be feasible but it again leads to sophisticated feedback system. Therefore, spatial control using state feedback would have been a better option for arbitrary pole placement. Again, practical implementation of such a controller would require a state observer which will increase the complexity. A better candidate would be the use of output information through modern control techniques such as Terminal Sliding Mode Control and its variants. However, in such applications, the intricacies associated with multi-timescale properties of the model need to be handled carefully.

3) Review of literature and development in the relevant subject

Flux Mapping Problem: Over the years, research has been carried out in development of most efficient flux-mapping algorithm for improved reliability, good accuracy in flux mapping with less computational effort. Flux Synthesis, Internal boundary condition, and simultaneous least squares solution of neutron diffusion and detector response equations are the few existing flux mapping algorithms available in the literature. Out of these, the Flux Synthesis Method (FSM) [6] is well known and traditional method for flux mapping. This method performs a least square fit with precomputed flux modes based on the available detector measurements and configuration and considerable insight into the reactor operation for determination of flux modes. Further, to enhance the accuracy of flux mapping, other synthesis methods such as the Harmonic Synthesis Method (HSM) [1, 8] and Harmonic Expansion Method (HEM) [2] have been developed in the recent years. But, the accuracy of reconstruction depends on selection of the reference case which is requires to be renewed during the core configuration changes. Thus this becomes a time-consuming process.

Another method known as the internal boundary condition based on direct online solution of neutron diffusion equations with detector readings is widely studied in the literature [8, 9]. Furthermore, a method based on least squares solution of the core neutronics design equations along with the in-core detector response equations is developed to estimate the most probable power distribution [10,11,12]. Applicability of this least squares method requires solving the over-determined system of equations resulting in the framework of mapping algorithm. A method based on the combination of FSM and least square method, known as the modified flux synthesis method has been proposed for the Indian 700 MWe PHWR [13]. But the resulting method is not much computationally efficient as detector signal uncertainty can deteriorate the performance of flux-mapping calculations [12]. The main drawback of these methods is that the accuracy of flux mapping is significantly degraded in presence of uncertainty in the detector readings and they fail to account for time variation of neutron flux modes during the reactor operation [14]. A common feature of these methods is the assumption that the neutron flux modes in the reactor is independent of time. Application of Kalman filtering-based approaches are also found though to a very limited extent.

Power Distribution Control Problem: Application of modern control techniques for spatial control of large nuclear reactors, like Pressurized Heavy Water Reactor and Advanced Heavy Water Reactor, becomes difficult because of interacting dynamic phenomena of widely different speeds, giving rise to widely separated groups of eigenvalues. In this situation, singular perturbation techniques prove to be superior. Application of singular perturbation approach to a different type of reactor control problem is given by Reddy and Sannuti [46]. Further, in [65], numerically ill-conditioned model of PHWR is decoupled into two subsystems based on singular perturbation technique. Subsystem regulator problems are designed separately and then they are combined to obtain the near-optimum composite control, for original model, for the regulation of spatial power distribution in the reactor core. As an extension to this, simultaneous decomposition of singularly perturbed three-timescale system of AHWR into three subsystems is achieved in [54]. These singular perturbation techniques eliminate numerical ill-conditioning issues associated with PHWR and AHWR. However, these methods require all the states for feedback. Several mechanisms for detection of neutron flux or power are known but there is not any instrument for measuring delayed neutron precursor, xenon, and iodine concentrations in the reactor. As a consequence of this, it is difficult to implement the control laws based upon modern concepts characterized by state variable feedback. To overcome this problem, a deterministic, linear, and reduced order observer has been designed in [63] for estimation of an average delayed neutron precursor, xenon, and iodine concentrations in different regions of the PHWR core. However, observer-based design results in complex structured

closed-loop system requiring expensive hardware and processing network which increase the implementation cost and reduces the reliability of control system. Hence, it is desirable to go for an output feedback design. Spatial control strategy based on static output feedback control (SOFC) has been attempted in [56] and it is shown that spatial stabilization of AHWR is possible with the feedback of total power and spatial power distribution signals. This technique is easy to implement. However, complete pole assignment and guaranteed closed-loop stability are still not obtained by using SOFC [61]. The dynamic output feedback controller involves more dynamics and is more complex to design.

In recent years, one of the robust control techniques named, sliding mode control (SMC) has attracted the attention of many researchers. Sliding mode spatial control of PHWR is documented in [42-45]. In [44], sliding mode observer is proposed to estimate the states of PHWR. Further in [42, 43, 45], MROF-based sliding mode control is proposed for PHWR. These methods do not require state information of the system for feedback purpose and hence may be easier to implement. Sometimes, it is required to design a closed-loop system which is fault tolerant in the sense that the stability is not lost even if sensors or control actuators have failed. Incorporating such a consideration in the design leads to multi-model plant description for which usual design methods are not tractable. Fault-tolerant spatial control systems for PHWR are presented in [49, 64]. Approach presented in [64] is based on POF whereas in [49] it is based on FOS. Spatial control means to suppress xenon oscillations from growing. A modified method based on the concept of three axial offsets has been presented in [50] for controlling xenon oscillations in large PWR. This method gives continuous information of oscillations in reactor to operator, which helps the operator to understand the situation rather clearly. As an extension to this, concept of monitoring and control of radial xenon oscillations in PWR has been suggested in [51], which utilizes feedback of not only axial offsets but also uses information of power reactor distribution in respective core regions. Further, similar kind of approach based on characteristics ellipse trajectory drawn by three axial offsets is proposed in [52].

Another promising method, fuzzy logic controllers (FLCs) for nuclear reactor applications [39-41] has been around some years. They provide a high degree of robustness and immunity to external disturbances. Furthermore, they can be configured to be self-learning and adaptive. A fuzzy model predictive control method [41] is used to design an automatic controller for thermal power control in PWRs. In this, the future reactor power is predicted by using fuzzy model identified by a subtractive clustering method of a fast and robust algorithm. The objectives of the presented fuzzy model predictive control law are to minimize both the difference between the predicted reactor power and the desired one, and the variation of the control rod positions. These objectives are subject to maximum and minimum control rod positions and maximum control rod speed. The genetic algorithm, useful to accomplish multiple objectives, is used to optimize the fuzzy model predictive controller. Recently, Londhe et al. [39] have proposed spatial control of AHWR using single-input fuzzy logic controller (SIFLC). The SIFLC reduces the conventional two-input fuzzy logic controller to a single-input FLC. It is shown that the SIFLC offers a significant reduction in rule inferences and simplifies the tuning of control parameters. Also, SIFLC requires less execution time compared to conventional two-input fuzzy logic controller for the control of spatial oscillations in AHWR. Further in [40], a simplified fuzzy like proportional derivative controller is proposed for spatial control of AHWR. Some other control techniques, based on discrete Proportional-Integral-Derivative (PID) and fractional order PID, are recommended in [31-33].

4) Objectives of the research and proposed hypothesis.

1. Developing new power distribution control methods based on sliding mode control such as terminal sliding mode control and its variants for AHWR.
2. Developing new flux mapping algorithms employing stochastic observer techniques such as variants of Kalman filter, H-infinity filter, sliding mode observer etc for AHWR.
3. Casting the available non-linear/linear space-time kinetics model of AHWR in a structure amenable to the technique/s under consideration.
4. Simulation of different steady state/transient operating conditions and comparison of accuracy of different algorithms.
5. Comparison of robustness and insensitivity of the algorithms to single/multiple detector failures through simulation of many possible combinations of such failures, and arriving at the upper bounds of simultaneous failures that can be tolerated by the algorithm.

5) Methodology to be used and adopted

The advanced heavy water reactor has to be studied and modeled for studying the flux mapping techniques. Existing techniques for flux mapping of AHWR are to be studied, reviewed and applied to the AHWR. New methods are to be developed for achieving robustness and accuracy under different steady state or transient operating conditions. Some new control strategies are to be developed for power distribution control of AHWR. Comparison of these strategies with existing techniques is to be simulated experimentally.

6) Importance of the study

It is economically desirable to operate a nuclear power reactor at or close to the designed power level. To achieve this, it is required to reconstruct the core flux (and power) distribution from the in-core neutron detector readings. This will ensure the reactor operating normally and safely. However, reconstruction of core flux distribution is very difficult task due to availability of partial/incomplete data when the number of in-core detectors is limited. Thus, the core may have an unpredictable departure from the nominal (designed) core, and the detector readings inevitably contain random errors. To ensure accurate flux reconstruction, over the years, the online Flux Mapping Systems (FMS) have been developed with the help of flux mapping algorithms. In Indian 540 MWe Pressurized Heavy Water Reactors (PHWRs), 102 vanadium detectors are used for flux mapping, while in PWRs it is carried out by rhodium detectors installed in about 45 fuel assemblies.

Most of the flux mapping algorithms are based on three principles, namely the Flux Synthesis, Internal boundary condition, a simultaneous least squares solution of neutron diffusion and detector response equations. Recently, a method based on the combination of Flux Synthesis Method (FSM) and least squares method, known as the modified flux synthesis method has been proposed for the Indian 700 MWe PHWR [28]. But the resulting method is not much computationally efficient as detector signal uncertainty can deteriorate the performance of flux-mapping calculations. The main drawback of the aforementioned methods is that the accuracy of flux mapping is significantly degraded in presence of uncertainty in the detector readings and also they fail to account for time variation of neutron flux distribution during the reactor operation.

By considering aforesaid weaknesses of flux mapping methods, an efficient flux-mapping algorithm [14] is proposed for Advanced Heavy Water Reactor (AHWR). AHWR is a 920 MW (thermal), vertical, pressure tube type, heavy-water moderated, boiling light-water cooled natural circulation reactor [25, 26]. Due to its large physical dimensions, operational perturbations might lead to slow xenon-induced oscillations. This might cause changes in axial and radial flux distribution from the nominal distribution. To monitor the core flux distribution, 200 SPNDs are proposed to be provided in AHWR. In [14], the flux-mapping problem of AHWR is formulated as a linear stochastic estimation problem for singularly perturbed systems [27] and the solution is obtained by the Discrete-Kalman Filtering

(DKF) technique. To address the numerical ill-conditioning problems in full-order design, a discrete-time decoupled Kalman filtering (DDKF) technique has been developed by decoupling the DKF equations according to the order of the slow and fast subsystems. Finally, this technique has been applied for estimation of detailed mesh, channel, and zonal fluxes in the AHWR.

Initially, a few decades ago, the flux mapping methods such as INCORE [29] and CECOR [30], have been proposed for reconstruction of flux distribution. These are basically interpolation methods and possess certain limitations such as their results may be greatly influenced by the random measurement errors and cannot be used to evaluate the core condition or to diagnose the core failure. To overcome these limitations, a new method called Harmonics Synthesis Method (HSM) [1, 7] is proposed. Further, to enhance the accuracy of flux mapping, other synthesis methods such as the Harmonic Expansion Method (HEM) [2] have been developed in the recent years. But, the accuracy of reconstruction depends on selection of the reference case which is requires to be renewed during the core configuration changes. As a result, this becomes a time-consuming process.

Another method known as the internal boundary condition based on direct online solution of neutron diffusion equations with detector readings is widely studied in the literature [8, 9]. Furthermore, a method based on a least squares solution of the core neutronics design equations along with the in-core detector response equations is developed to estimate the most probable power distribution [10, 11, 12]. Applicability of this least squares method requires to solve the overdetermined system of equations resulting in the framework of mapping algorithm. But the resulting method is not much computationally efficient as detector signal uncertainty can deteriorate the performance of flux-mapping calculations [12]. The main drawback of the aforementioned methods is that the accuracy of flux mapping is significantly degraded in presence of uncertainty in the detector readings and they fail to account for time variation of neutron flux distribution during the reactor operation. A common feature of these methods is the assumption that the neutron flux profile in the reactor is independent of time. Application of Kalman filtering-based approaches are also found though to a very limited extent. The new improved technique will help in achieving efficient in-core flux mapping and fault tolerant design, thus improving the overall economy of operation.

Recently, multirate output feedback (MROF) has drawn much interest of many researchers and the application to nuclear reactor for spatial control is successfully demonstrated. In contrast to observer-based design in which accuracy of estimation of states improves after long time, exact computation of states in just one sampling period is feasible if MROF is employed. In MROF, sampling rates of input and output are different. In one type of MROF technique culled periodic output feedback (POF), the input is sampled at faster rate than the output. In the other type of MROF called fast output sampling (FOS) feedback, output is sampled faster than the input. Application of periodic output feedback, control for PHWR is reported in [62, 66]. In [66] using linear transformation of state variables, the singularly perturbed model of PHWR is converted into a block triangular form in which the fast subsystem is decoupled. Then, an output injection gain matrix stabilizing the slow subsystem is obtained. The periodic output feedback gain is subsequently calculated only for the slow subsystem and the same for the fast subsystem is set equal to zero. Finally, the POF gain for the composite system is obtained using the POF gains computed separately for the slow and fast subsystems. A decentralized periodic output feedback is proposed for PHWR in [62], which proves to be simpler for practical implementation. Fast output sampling technique for PHWR and AHWR is suggested in [47, 48, 55]. A robust controller for uncertain systems using FOS technique is examined for PHWR in [48]. The FOS control allows the realization of the robust state feedback gain simultaneously for family of linear models. The issues of noise sensitivity and error dynamics are overcome by posing the problem as linear matrix inequality problem in [47], the discrete system of PHWR is transformed into block diagonal form in which slow and fast subsystems are decoupled. State feedback control is designed for the slow subsystem while the state feedback for fast subsystem is taken as zero. Then, composite state feedback controller is obtained and it is realized by fast output sampling feedback gain. The technique presented in [48] is extended for three-timescale system and has been successfully applied to AHWR in [55]. However, these methods lack robustness. Also, these control techniques nay not work satisfactorily in presence of disturbances, parameter variations and perturbations in the operating conditions. Robust control techniques could be useful in such situations.

In the context of power distribution control in a nuclear reactor, it is worth mentioning that the model of a nuclear reactor belongs to a special class of systems called singularly perturbed systems. The simultaneous presence of both the slow as well as fast varying dynamical modes, could cause ill-conditioning of the problem. Fortunately, the rich

literature on singular perturbations and control makes it feasible to analyze such systems and design the controller. The model of the nuclear reactor can be transformed into a suitable form whereby stiffness is completely eliminated. Besides, model reduction can be achieved to certain extent. Once, this has been done, numerous approaches are available for carrying out the design of power distribution control systems.

7) Proposed work plan- with a tentative chapter scheme

- Chapter 1: Introduction and Literature Survey
- Chapter 2: Modeling of AHWR
- Chapter 3: Terminal SMC for Power Distribution Control
- Chapter 4: Higher order SMC for Power Distribution Control
- Chapter 5: Kalman Filter variants for Flux Mapping
- Chapter 6: Sliding Mode Observer for Flux Mapping
- Chapter 7: H-infinity filter for Flux Mapping
- Chapter 8: Comparative study of algorithms
- Chapter 9:Conclusion

8) Year wise plan of work and targets to be achieved

Sr. No.	Year 1	Year 2	Year 3
1	Literature Survey of Nuclear Reactor Theory, Modeling of AHWR and implementation in MATLAB	Study and development of H-infinity filter for flux mapping	Simulation of different steady state/transient operating conditions
2	Study of stochastic observer techniques such as Kalman Filter variants for flux mapping of AHWR	Study and development of Sliding mode observer for flux mapping	Comparison of accuracy, robustness and insensitivity of the algorithms against single/multiple detector failures
3	Study and Design of Terminal Sliding Mode Controller for Power Distribution Control	Design and Development of Higher order SMC for Power Distribution Control	Preparation of Report

9) Expected outcome

1. Implementation of nonlinear model of AHWR for flux mapping
2. Implementation of flux mapping algorithms for AHWR
3. Simulation of different steady state/transient operating conditions and comparison of modern flux mapping methods
4. Implementation of power distribution control strategies for AHWR
5. Comparison of robustness and insensitivity of the proposed algorithms

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